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RESEARCH ON CONTROLLED THERMONUCLEAR REACTIONS IN THE U.S.S.R.

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INTRODUCTION

1. The idea of using controlled thermonuclear reactions for power generation by exploiting the fusion of light nuclei has been proposed many times in the past. However, it is only after many years of preliminary work, the results of which were not immediately obvious, that a basis had been laid for justifying the hope that a successful solution for this problem could be realized. There has been a rapid expansion of the scale on which research in this field is being carried on and at the present time the development of methods of obtaining controlled thermonuclear reactions is one of the most important problems in nuclear technology.

An important factor in the rapid development of scientific research in this field was the removal of rigid secrecy restrictions which had earlier isolated physicists working on this problem in different countries. As long as the prevailing opinion was that the danger of publishing scientific results was greater than any advantage which could be obtained by exchanging scientific information, the research work proceeded slowly. A significant change took place in 1956 when the results of work carried on in the U.S.S.R. were communicated for the first time. These disclosures were followed by the gradual publication of the results of research carried on in England and the U.S.A. It then became possible to carry on an exchange of ideas and experiences and this was of incalculable value, especially for a project of such scientific and technical difficulty as that of attaining a controlled thermonuclear reaction.

In spite of the wide range of research on controlled thermonuclear reactions, at the present time all approaches to this problem are more or less in the exploratory stage. No one approach has been definitively evaluated. The one thing that is apparently agreed upon by all concerned is that the solution of the problem will require a method in which the confinement of a hot plasma is realized by means of a strong magnetic field.

2. The methods of using a magnetic field for confinement and heating of a plasma can be divided into two basic classes. One class consists of methods in which the plasma is accelerated by electrodynamic forces; the other consists of methods of producing equilibrium plasma configurations, i.e., states in which the pressure of the plasma is balanced by magnetic pressure. The difference between these two general methods can be seen more clearly if we express these ideas in terms of magnetohydrodynamics. As is well-known, magnetohydrodynamics is concerned with the general behavior of a conducting fluid in a magnetic field. Under certain conditions, which we shall assume satisfied, a plasma may be considered, from the macroscopic point of view, to be a conducting fluid. The equation that describes the behavior of a plasma subjected to electrodynamic forces is of the following form:

$$\rho \frac{d\mathbf{v}}{dt} = \frac{1}{c}\,\mathbf{j} \times \mathbf{H} - \operatorname{grad} p. \qquad (1)$$

The quantities $\mathbf{v}$ and ρ denote respectively the velocity and density of an elementary volume of the plasma, which moves under the action of the electrodynamic forces and the pressure differential. All terms in the equation refer to a unit volume of the plasma. The electrodynamic force operating on a unit volume of the plasma is represented by the first term on the right side of the equation. This term is due to the interaction between the magnetic field and the currents that flow in the plasma ($\mathbf{H}$ is the field intensity and $\mathbf{j}$ is the current density).

Examination of this equation reveals that two limiting cases can be considered, each characterizing a large class of confinement methods.

If the gas kinetic pressure is relatively small, the electrodynamic force is balanced by "inertial forces":

$$\rho \frac{d\mathbf{v}}{dt} = \frac{1}{c}\,\mathbf{j} \times \mathbf{H}.$$

Under these conditions, the electrodynamic forces can impart to the plasma as a whole a directed velocity that can exceed significantly the random thermal velocities of the ions. The kinetic energy of the directed motion acquired by the plasma in its acceleration in the magnetic field can be used for subsequent heating in processes such as compression, impact of accelerated plasmoids on a target, etc. Specific applications of these techniques will be described below.

A feature of this type of interaction between the plasma and a magnetic field is the short duration of the process. In order-of-magnitude terms this quantity is a/v, where a is the distance traversed by the plasma under the action of the accelerating forces and v is the velocity achieved. In cases of practical interest the duration of the acceleration process is on the order of $10^{-5} - 10^{-6}$ sec. It is apparent that pulsed processes of such short duration are of interest only if they can be used in the primary phases of plasma heating. These processes must result in the transformation of kinetic energy into heat and a transition to some quasi-stationary state in which the rapid inertial motions which continue after the first phase are damped out rapidly.

The other limiting case is that in which the acceleration of the plasma is small and the "inertial term" on the left side of the equation can be neglected compared with the pressure gradient. In this case the gas kinetic pressure and the magnetic pressure balance each other at all times:

$$\operatorname{grad} p = \frac{1}{c}\,\mathbf{j} \times \mathbf{H}.$$

It is possible to think of a number of different ways of realizing equilibrium plasma configurations, characteristic of a quasi-stationary state of the plasma in the magnetic field. At the present time the following more-or-less clearly defined trends seem to be developing:

(a) methods for confinement and heating of a plasma in systems with high discharge currents maintained by external voltages and stabilized by external magnetic fields;

(b) magnetic-trap methods, in which high-temperature plasmas are produced by the accumulation of fast particles injected into a trap.

This classification of the methods of obtaining and maintaining high temperatures in a plasma is obviously arbitrary; however, it is rather well suited to the purposes of the present paper since the divisions indicated here correspond to the basic approaches being used in the U.S.S.R. for research into controlled thermonuclear reactions.

3. Before describing some actual results obtained in the theoretical and experimental research carried out along the lines indicated above, we shall consider certain general characteristics that relate to the future of all thermonuclear reactors. Obviously any discussion of this kind, at the present stage of our knowledge, is based on our faith in the ultimate triumph of human ingenuity in this problem.

First of all, it must be noted that any magnetic-confinement system proposed for a solution to the problem of obtaining thermonuclear power must satisfy one basic requirement: the energy evolved in nuclear fusion must exceed the energy consumed from other sources used to maintain the high temperature in the plasma.

A simple analysis will show that this requirement can be written in terms of the following relation between the basic parameters which describe the performance of a thermonuclear generator:

$$H^2\tau > A\,(1-\eta). \qquad (2)$$

In this formula H is the intensity of the magnetic field that confines the plasma, and τ is the time during which the high temperature is maintained in the plasma. The quantity η denotes that fraction of the thermal energy of the plasma which is transformed into electrical energy over the cycle. The constant A depends on the nuclear fuel. Under most optimistic assumptions concerning the processes which take place in a thermonuclear generator this constant may be taken as 10^{10} if pure deuterium is used and 10^8 if a mixture of D and T, in equal proportions, is used. These values are based on the assumption that the thermonuclear reactions in the plasma occur at the "optimum" temperature; in deuterium this temperature is 50 kev (5×10^8 degrees) and in a D-T mixture, 15 kev (1.5×10^8 degrees).

In applying (2) with the indicated values for A one must keep in mind the fact that, strictly speaking, this relation describes only the ideal case, in which particles do not escape from the plasma under high-temperature conditions. In turn, this implies that the particle lifetimes are the same as the time during which the high temperature is maintained in the plasma.

As follows from Eq. (2), the shorter the time interval during which the high-temperature is maintained, the higher the required intensity of the magnetic field. In order for these requirements to be satisfied by present-day electrical facilities, it is necessary to use a method which permits confinement of fast particles in a plasma for periods of time that may be several seconds or even tens of seconds. Thus, if we assume that $\tau = 10$ sec the field intensity required in a pure-deuterium generator is on the order of 30,000 oersteds. A field intensity of this kind is within the capabilities of stationary apparatus. It should be noted, however, that in this case the power generated per unit volume of the generator would be small; for a complex machine of this kind to be of technological usefulness it would have to be of enormous dimensions.

4. We now consider the problem of direct conversion of thermonuclear energy into electrical power. The energy evolved as a result of the fusion process consists of two parts, which play roles of greatly differing importance in the operation of a thermonuclear generator. The fraction of the energy carried away by neutrons has no effect on the processes that take place in the plasma. In the computation of the electrical energy balance for the generator this factor is of the order of 0.3 (i.e., the same as that which applies for the energy generated in ordinary nuclear power stations that use fission of heavy nuclei). The other part of the nuclear fusion energy, which appears in the formation of high-energy charged particles, is released directly into the plasma, causing a temperature rise that can be converted into electrical energy with an efficiency close to unity.

The possibility of direct conversion is due to the fact that in magnetic confinement the high-temperature nuclear fuel is surrounded by a strong magnetic field, which acts very much like an elastic shell in compressing the plasma. If the high-temperature plasma expands, its thermal energy is used to do work against the magnetic pressure and is thus converted into electrical energy. If the maximum temperature of the plasma at the onset of expansion is T_1 and the minimum temperature to which the plasma is cooled at the end of each working cycle is T_2, the maximum value of η is given by the well-known formula

$$\eta = 1 - \frac{T_2}{T_1}.$$

From this it follows that in principle the quantity η can be very close to unity, inasmuch as the upper temperature in the thermal cycle is very high, making the ratio T_2/T_1 extremely small.

It should be kept in mind, however, that a substantial reduction in temperature during expansion can be realized only at the expense of an increase in the volume occupied by the plasma. In adiabatic expansion the temperature is inversely proportional to $V^{2/3}$, where V is the volume occupied by the plasma. Hence, to convert a significant part of the thermal energy of the plasma into electrical energy the volume occupied by the plasma must be increased by a large factor. This means that during the time at which the plasma is at maximum temperature, and is a source of thermonuclear power, it must occupy a very small part of the volume of the vacuum chamber in the thermonuclear generator; the remaining volume must be filled solely by a strong magnetic field. Thus, when η is close to unity only a small part of the generator volume is used efficiently; for this reason a compromise value of η, probably less than 0.75, must be used.

The basic advantage of the direct conversion of thermal energy of the plasma into electrical energy lies in the fact that in this method the utilization of the thermal energy of the plasma is characterized by a huge reduction in the irreversible thermal losses (which are proportional to $1 - \eta$). In addition, the operating conditions in the system are more favorable from the thermal point of view because the thermal load on the walls of the plasma chamber is reduced.

The total amount of energy produced by a thermonuclear generator should not depend on whether direct conversion of thermal energy to electrical energy is used or whether this conversion takes place by means of an intermediate heat transfer agent. This is easily seen if it is recalled that a large part of the energy released in nuclear fusion is carried away by the neutrons, and cannot therefore be directly converted into electrical energy.

5. The development of methods of launching controlled thermonuclear reactions are based on the supposition that the cource of energy must be deuterium or a mixture of deuterium with tritium. Of these two nuclear fuels, it would seem that in the future the D-T mixture will be the important one. The chief advantage of this mixture is the high effective cross section for the reaction. Over the entire temperature range of practical interest, the reaction yield for a D-T mixture (equal amounts) exceeds the reaction yield for pure deuterium by two orders of magnitude. Although the tritium obtained from conventional nuclear reactors is very expensive at the present time, this factor will only be a temporary barrier to its utilization, since there are methods that can be used to compensate for the tritium losses in a thermonuclear generator.

In each elementary D-T reaction event one tritium nucleus disappears and a fast neutron (14.1 mev) is produced and subsequently leaves the plasma. If the thermonuclear generator is surrounded with a thick layer of material in which the (n, 2n) reaction is induced by fast neutrons, it is possible to increase the primary neutron flux significantly. Neutron multiplication via the (n, 2n) reaction can be accomplished through the use of beryllium or heavy elements such as lead or bismuth. In these elements the cross section for the (n, 2n) reaction for neutrons at 14.1 mev is much greater than the cross sections for competing nuclear reactions. If any one of these materials is used as a blanket for the reactor the number of neutrons should increase by a factor of 1.5 or 2. This increase in the neutron flux can be used for breeding tritium by disintegration of Li^6. An analysis of the data referring to the (n, 2n) reactions and the tritium producing reactions indicates that even for very conservative estimates the tritium breeding ratio in a thermonuclear reactor can easily be made greater than unity.

Thus, in working with a D-T mixture it should be possible to realize conditions for which the supply of tritium increases in the course of time. Hence, as long as there is no danger of exhausting the available supplies of Li^6 thermonuclear reactors can be operated with a D-T mixture and also used to regenerate tritium. It should be added that even if for some reason it becomes necessary to give up the regeneration of tritium and work with deuterium the principle energy effect will still be obtained from the tritium formed in the D-T reaction.

At this point we turn to an examination of the results of the experimental and theoretical research carried on in the U.S.S.R. on the problem of controlled thermonuclear reactions in the past few years. Our attention will be directed chiefly to the results of new work which has not yet been discussed widely. The material will be considered in accordance with the research classifications indicated above.

I. FAST PULSED PROCESSES

6. Up to this time, the major effort in the study of fast pulsed processes has been concentrated on the features of intense pulse discharges in deuterium at low pressure. The main idea here is to obtain a high temperature and a high density in a compressed plasma column for a short period of time. Investigation of pulsed discharges with a very high rate of rise (from 10^{10} to 10^{11} amp/sec) has shown that whether or not such discharges take place in straight tubes or in toroidal chambers, the important factor is the acceleration of the plasma by electrodynamic forces. In the initial phases of a pulsed discharge the plasma contracts to the axis of the discharge tube; this contraction is the first stage in the rapid oscillations of the plasma pinch. The maximum temperature and density are achieved at the time at which the plasma pinch is of minimum radius.

The theoretical analysis of effects that take place in a plasma in pulse discharges has passed through two states. At first a very simple model was used for a qualitative explanation of the dynamics of a plasma pinch. The motion of the mass of ionized gas was analyzed as a whole under the effect of the given electrodynamic forces. In the next stage of development an attempt was made to carry out a more rigorous quantitative analysis of the contraction and oscillation of the plasma column, taking into account the formation of shock waves in the plasma and the time variation in the mass of the moving gas. This calculation was carried out in the magnetohydrodynamic approximation, in which the plasma is considered a monatomic gas with constant conductivity. Even in this idealized form the problem leads to a complex system of partial differential equations, which can only be solved by numerical integration in large electronic computers.

The solution of this problem yields data on the density, temperature, and drift motion for each segment of the plasma column at various moments of time as well as data on the distribution of current density and magnetic and electric field. The amount of information of this kind is considerably greater than that which can be obtained from experimental studies of plasma properties. However, it is possible to check the theoretical results at a number of important points by making comparisons with the experimental data. Comparisons of this kind can be made for the distribution of current density and radial plasma velocity since these features of the process are amenable to experimental measurement. Comparisons of this type between experiment and theory, which have been carried out for a number of particular cases have, generally indicate satisfactory agreement at least as regards the initial stages of the pulsed process (up to the second contraction). For this reason there is some justification in using the results of the theoretical calculations to estimate quantities which are difficult to measure experimentally with the required accuracy. The most important of these plasma characteristics are the temperature under the maximum implosion conditions of the shock wave and the distribution of matter at this instant of time.

The numerical calculations indicate that the following equation can be used to estimate the lower limit of the temperature at the time of the first contraction:

$$\overline{T} = 4.6 \cdot 10^{12} \frac{I^2}{N}, \qquad (3)$$

where I is the current strength in kiloamperes at this instant of time and N is the number of particles of a given sign per unit length of pinch. This equation gives the mean plasma temperature value (in kev) on the assumption that there is ideal heat exchange between the ions and electrons. The radial temperature distribution for a pinch is shown schematically in Fig. 1. The dashed line represents the mean value of T. Because of the cumulative effect produced by the incident shock wave, at small distances from the axis the temperature

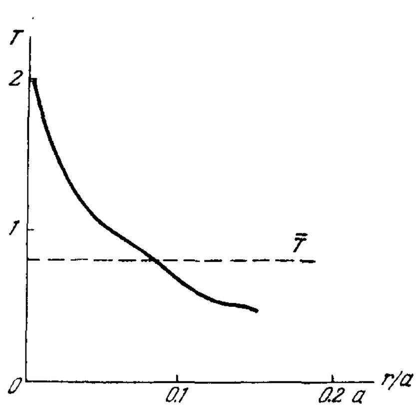


FIG. 1

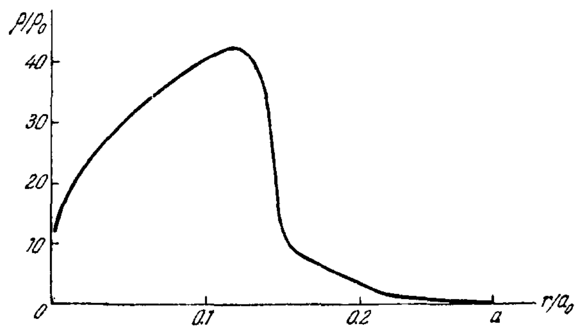


FIG. 2

increases sharply and exceeds the mean value by a large factor. If we also note that under typical experimental conditions thermal equilibrium between the ions and electrons is achieved at maximum contraction only when $T < 0.1$ kev, it becomes apparent that the formula given above corresponds to a very conservative estimate of ion temperature in an actual pinch. Therefore we can use it with confidence in estimating the lower limit of the temperature achieved in the latest experiments with high-power pulsed discharges.

Figure 2 shows the density distribution of matter at the implosion maximum. The maximum density at this instant of time exceeds the initial gas density by a factor of 30 or 40. One of the interesting features of the theoretically determined density distribution is the diminution near the axis. This type of density variation is directly related to the temperature rise near the axis (the pressure, which is proportional to ρT, should level off in this region).

7. Experiments carried out in recent years on high-power pulsed discharges have generally been following the trends of earlier research, the results of which were published in 1956 and are well known. In these recent experiments much attention has been devoted to improving the various discharge parameters with the purpose of achieving higher temperatures.

Improvements in the construction of spark-gaps and in the power systems have made it possible to increase the voltage per unit length of discharge tube and to reduce the stray inductance of the circuit. As a result it has been possible to increase the rate of rise of the current and the current during the first contraction (500 kiloamperes in a discharge tube 50 cm long and 40 cm in diameter). In Fig. 3 is shown the dependence of temperature in a plasma pinch on the initial voltage applied to the discharge tube for a tube filled with deuterium at an initial pressure of 0.05 mm Hg. The temperature has been computed from Eq. (3) which, as has been indicated above, yields values which are too low. For this reason we can assert with confidence that in these experiments temperatures exceeding 3 or 4 million degrees were certainly attained. In particular, it may be assumed that the neutron radiation obtained under these conditions is due, in large degree, to thermonuclear reactions.

In this connection it should be noted that in these enhanced power reactions neutrons appear immediately after the first contraction phase, i.e., at the time at which both the temperature and density are at a maximum; the neutron pulse extends over a period on the order of a microsecond.

At the present time, however, the proof or disproof of the thermonuclear origin of a small burst of neutron radiation in a pulse discharge is not important enough to warrant special attention. For this reason I do not think it is necessary to insist that thermonuclear reactions have actually been observed in the experiments mentioned above. The question of whether or not a given neutron belongs to the noble race descended from thermonuclear reactions or whether it is the dubious offspring of some disreputable acceleration process is something which may upset the representatives of the press, but at the present stages of the problem, should not disturb scientists. When the number of neutrons produced in one discharge pulse becomes greater than 10^{12}, any doubts as to the origin of this effect will be dispelled.

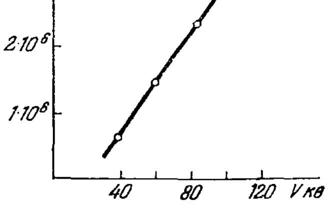


FIG. 3

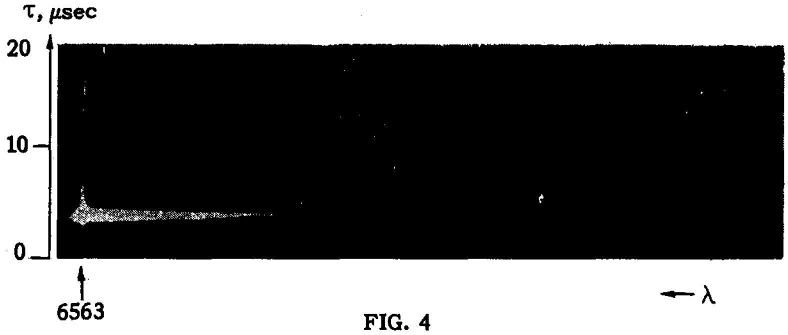


FIG. 4

However, to attain intensities of this kind in thermonuclear neutron radiation in pulsed discharges, it will be necessary to carry on experiments with circuits in which the values of the parameters are much higher than has been the case heretofore. The chief difficulty in this respect is that any further increase in the power of a pulsed discharge is limited by heating of the chamber walls. To a certain degree this difficulty can be overcome by using chambers with sectionalized metal walls. However, attempts should be made to investigate other methods: for instance, magnetic shielding of the walls and use of vacuum chambers with local injection of directed gas streams.

In addition to the aforementioned series of experiments with high-power discharges, a number of other investigations have been carried out to study the various properties of the high-temperature plasma in a pulsed discharge. There have been many advances in spectroscopic investigations of plasma. After a method was developed for obtaining streak photographs of discharge spectra it was found that at the time of the first contraction there is a sharp increase in the continuum over the entire range. This flash is shown clearly in the photograph in Fig. 4, which is a streak photograph of the spectrum of a discharge in hydrogen with an initial pressure of 0.1 mm Hg and an initial voltage of 35 kv. The continuum flash is explained by the fact that at maximum contraction there is a discontinuous rise in the plasma ionization and this results in an increase in the concentration of free electrons. In turn these cause intense bremsstrahlung and recombination radiation. By measuring the intensity of the continuum in a given spectral range it is possible to make a fairly accurate measurement of plasma density (under the assumption that total ionization obtains).

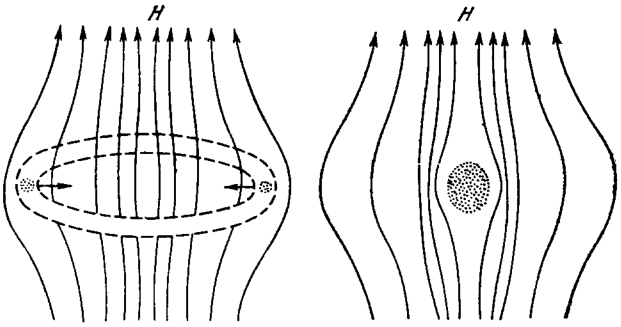
The calculations indicate that, because of fortuitous circumstances in the numerical values, the intensity of the radiation is very insensitive to electron temperature. For this reason any arbitrariness in the choice of electron temperature has essentially no effect on the determination of density by means of measurements of the spectral continuum. Density measurements carried out in this way yield results which are in good agreement with the values obtained from magnetohydrodynamic theory.

Spectral observations also make it possible to evaluate the plasma temperature from the Doppler broadening of impurity lines. As yet this method has been applied only to discharges under standard conditions (initial voltage 35 kev, hydrogen pressure 0.05 mm Hg, tube length 90 cm). Under these conditions the plasma temperature at maximum contraction as determined from the width of the nitrogen line (λ 3479 A) is found to be approximately 100 ev, as compared with the 65 ev predicted from Eq. (3).

The aim of a number of investigations has been the determination of the properties of the hard radiation produced in the plasma and the mechanism responsible for this radiation. Cloud chambers have been used to study the spectrum of electrons which are produced by the hard x-rays from pulsed discharges. These studies have confirmed the maximum x-ray energies which had been estimated earlier (350 — 400 kev).

Mass-spectroscopic analyses of the fast particles produced in the discharge have also been carried out successfully. The parabola method has been used to measure the e/m ratios and the energies of ions which are extracted from the discharge chambers through apertures in the side walls or in the electrodes. It has been established that the neutron energy is as high as 200 kev.

In discussions of the possible mechanisms which lead to the appearance of hard radiation it has frequently been asserted that an important role is played by "sausage" type instabilities which enhance the implosion of the shock wave. To verify these suggestions, experiments have been carried out in discharge geometries in which the conditions have been such as to make the contracting plasma assume an essentially spherical shape. These experiments have yielded interest-



a) FIG. 5 b)

ing results and indicate that the artificial creation of spherical implosions in a contracting plasma changes the characteristics of the hard radiation to a marked degree.

We may dwell briefly on the question of the future of methods of generating thermonuclear reactions in which powerful pulsed discharges are used. From the purely physically point of view, in the final analysis everything depends on two basic characteristics of the pulsed discharge:

(a) the degree of contraction of the pinch, which is characterized by the minimum value of the pinch radius a;

(b) the time duration of the contraction state τ.

It is easy to see that the power efficiency of a pulsed discharge, viewed as a thermonuclear reaction source, is proportional to the square of the current strength and the quantity τ/a^2. Theoretical estimates of the numerical values of τ/a^2 for very intense pulsed devices differ by more than two orders of magnitude, depending on the degree of optimism which implicitly or explicitly enters into the initial stages of the calculation. However, even with optimistic assumptions it turns out that the efficiency of a pulsed thermonuclear reactor can approach unity only if an enormous amount of energy is concentrated in the system (the order of 10^{10} joules for operation with a D-T mixture). This energy is initially stored in the power sources and then, in a brief time interval, is converted to a considerable degree into thermal and mechanical energy of the expanding plasma. This stage of the process must have the properties of a powerful explosion (at least equivalent to the explosion of 10 tons of TNT). At the present level of technological development we do not have available methods of making use of explosive energy of this kind and do not know of means of protecting the cumbersome and extremely expensive apparatus from possible destruction after each pulse. Nevertheless, it is still believed that research on pulsed discharges should be carried out at a higher technological level than has been achieved so far; it will be of interest to reach current rates of rise of the order of 10^{13} amp/sec under conditions in which the gases evolved from the walls of the discharge chamber have no effect on the initial stages of contraction. Experiments of this kind are not beyond the limits of present-day technological feasibility. Moreover, they may lead unexpectedly to the discovery of new factors which may have important effects on the general development of research in this field. Work on powerful fast discharges has been carried out mainly at the Institute for Atomic Energy of the U.S.S.R. Academy of Sciences. Certain problems in this field have also been studied at the Physics Department of Moscow State University. Experimental research on other types of pulsed processes in which a plasma interacts with a strong magnetic field have also been carried out at the Institute for Atomic Energy of the U.S.S.R. Academy of Sciences, the Ukrainian Physico-Technical Institute, and the Sukhumi Institute of Electron Physics.

Plasma acceleration by electrodynamic forces is realized in its purest form in accelerators such as the electrodynamic gun. The simple principle underlying devices of this kind is the following. A plasmoid, produced by the passage of a high current through a fine wire or a gas cloud, is accelerated along metal rails by virtue of forces due to the interaction of the current with the magnetic field produced by the conducting feeders (or, in another version, with an external magnetic field). Experiments have shown that in systems of this kind it is possible to achieve plasma velocities up to 5×10^7 mm/sec without any great effort. It is more than likely that even higher velocities will be achieved.

Another method of obtaining plasmoids has been studied at the Institute for Atomic Energy. This method is as follows: first a circular plasma loop containing a current is formed in an alternating external magnetic field, the lines of force of which are perpendicular to the plane of the loop (Fig. 5). This loop is produced by virtue of the breakdown of the gas in the induced electric field which accompanies the buildup of the H field. After a certain time interval, following the formation of the loop, the loop starts to contract rapidly toward the axis and changes into a plasmoid. Experiments indicate that with this method it is possible to obtain particle densities of 10^{16} and initial temperatures greater than 100 — 200 ev. One of the practical consequences of these experiments may be the development of a method of injecting hot plasma into a magnetic trap.

It may also be possible to realize a pulsed thermonuclear reaction under conditions in which the high temperature is reached by contraction and implosion produced not by electromagnetic forces, but by a charge of conventional explosive (such as TNT or something more powerful) which surrounds a capsule containing deuterium or a mixture of deuterium and tritium. Without dwelling on the experimental details, we may note that conditions have been found under which the generation of neutrons in D-D and D-T reactions have been established reliably and reproducibly. The detection apparatus is destroyed in these experiments. However, the signal from the neutron pulse reaches the buildings housing the detection system (which were located at a distance) before the buildings are destroyed. In experiments carried out in 1952 recordings were made of fast neutrons which passed through the charge without any great loss of energy and neutrons which were slowed down in the explosive and then entered the recording apparatus, forming a pulse which extended over several tens of microseconds. Obviously, in this case the notorious question of whether these neutrons are thermonuclear or not does not enter. There is no doubt that in this case we have observed neutrons which are formed as a result of the heating of matter to extremely high temperatures.

The chief difference between this process and electromagnetic contraction is that the former takes place under conditions in which the density of matter is very high (significantly exceeding the normal density of solids). The brief duration of the heating process makes it possible to dispense with the use of magnetic confinement. It is apparent that this process can be of economic interest only if the release of thermonuclear energy can balance the cost of the expensive explosive materials.

Just as in the case of large pulses of electrical power [with power yields up to ten tons of TNT (cf. above)], the practical exploitation of explosive heating involves difficulties associated with the explosive nature of the process.

II. SLOW PULSED DISCHARGES IN TOROIDAL CHAMBERS

8. It is to be expected that there should be fundamental differences when the current in a plasma builds up at a slow rate as opposed to the case in which the current rises at a fast rate. A quantitative criterion which can be used to distinguish between "slow" and "fast" discharges is the ratio of the current rise time to the period of the inertial radial oscillations of the pinch. In rarified gas discharges with maximum current strengths of the order of $10^5 - 10^6$ amp, hundreds of inertial oscillations can take place during the first half-period (of the order of 10^{-3} sec). Such discharges may be called slow, in contrast with fast discharges in which only two or three radial oscillations take place in the time the current reaches its peak value.

In slow discharges one may expect the electrodynamic forces to balance the gas kinetic pressure of the plasma with the plasma temperature being increased by virtue of Joule heating. In order for this equilibrium state to be useful for the heating of plasma to very high temperatures the following conditions must be satisfied:

(a) the pinch must not come in contact with the walls;

(b) the equilibrium state must be a stable one.

Theoretical investigations of equilibrium conditions and of the stability of pinches and their heating characteristics have been carried out at the Institute for Atomic Energy under the direction of M. A. Leontovich. It was first shown in this work that stability of a plasma pinch with more or less sharply defined boundaries can be obtained only when the discharge chamber is enclosed in a conducting sheet (close to the chamber walls) and when, in addition to the field set up by the plasma current, there is also a stabilizing magnetic field in the direction of the pinch (which must be set up by external coils). Two different stability modes are found. The first obtains when the contracting plasma column entrains a large part of the magnetic flux of the longitudinal field which exists initially in the discharge chamber ("paramagnetic pinch"). In this case the intensity of the longitudinal field inside the pinch is approximately $H_0(b/a)^2$, where H_0 is the initial intensity of the field and the quantities b and a denote respectively the inner radius of the discharge chamber and the radius of the pinch.

As is well known, this mode has been investigated in detail by British physicists working with the Zeta system. From the theoretical point of view this approach seems to be most promising as far as stabilization of the shape and dimensions of the pinch are concerned. In the magnetohydrodynamic approximation the main requirement for stabilization of all dangerous perturbations of a highly conducting pinch is the requirement that H_z inside the pinch be rather close to the field intensity of the current at the boundary of the pinch and that it be several times greater than the strength of the longitudinal field beyond this point (cf. Fig. 6, in which is shown schematically the distribution of longitudinal field H_z and current field H_φ). Another requirement is that the pinch radius a must not be too small as compared with

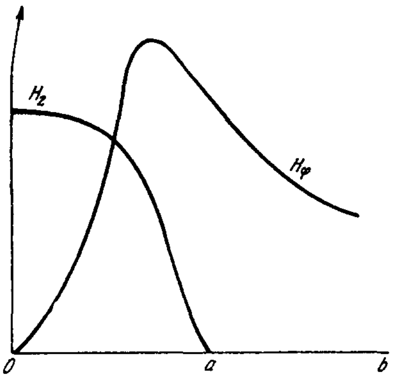


FIG. 6

the chamber radius; if this is not the case the stabilizing effect of the conducting sheet is no longer realized.

A relatively small initial value for the initial longitudinal field H_0 is sufficient for realizing this mode of operation. Another advantage is the fact that this mode of operation is one which arises naturally during the course of a pulsed discharge which is initially spread over the whole cross section of the chamber; later, as H_φ becomes comparable with H_0 the discharge contracts, entraining the longitudinal force lines. From the theoretical point of view, however, there are certain disadvantages associated with this mode of operation. To achieve stability of a paramagnetic pinch the quantities H_z and $H_\varphi(a)$ must be approximately the same. Hence, only a small part (0.3 — 0.4) of the electrodynamic pressure produced by the current is useful for counteracting the gas kinetic pressure. This means that at equal values of I and N the temperature of a paramagnetic pinch will be several times smaller than that which obtains in the case in which the longitudinal field is distributed uniformly over the cross section of the discharge chamber. It should also be noted that in order to obtain good heat exchange between electrons and ions in the paramagnetic mode the minimum value of N must be at least an order of magnitude greater than in the case in which a field is not captured.

The magnetohydrodynamic analysis also predicts the possibility of another stable discharge mode in which stabilization of the pinch is achieved by virtue of a strong longitudinal magnetic field of strength H_z which is everywhere larger than H_φ. In this case the theory indicates that the criterion for stability is the satisfaction of the inequality

$$\frac{H_z}{H_\varphi} > \frac{L}{2\pi a}, \tag{4}$$

where L is the length of the pinch (for a circular pinch in a toroidal chamber of radius R this quantity is $2\pi R$).

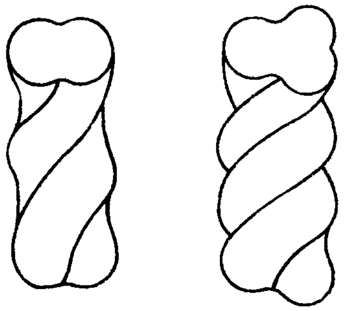


FIG. 7

However, even when this requirement is satisfied certain types of perturbations can still lead to instabilities. The nature of these perturbations is shown schematically in Fig. 7. It would seem that these are not too dangerous since they do not involve a displacement of the pinch axis.

In the case being considered here the longitudinal magnetic field is distributed over the entire cross section of the chamber and does not change appreciably near the pinch boundary (cf. Fig. 8). An advantage of this method of stabilization is the fact that the time during which it is realized does not depend on the skin-effect period but only on the time during which H_z and I are maintained. Another advantage is the possibility of obtaining a much higher ion temperature for a given current strength than is the case in the "paramagnetic" mode. However these advantages must be viewed in terms of the high cost involved in the need for operation at very strong magnetic fields. In order to approach the threshold of the temperature region of interest it is necessary to produce magnetic fields of the order of 3×10^4 to 5×10^4 oersteds over very large volumes and very considerable technological difficulties are involved in producing such fields. Difficulties are also encountered in bringing the system up to this level of operation.

The results of the magnetohydrodynamic analy-

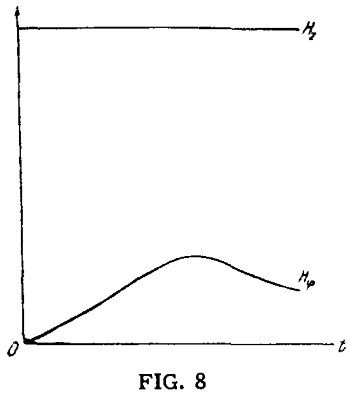


FIG. 8

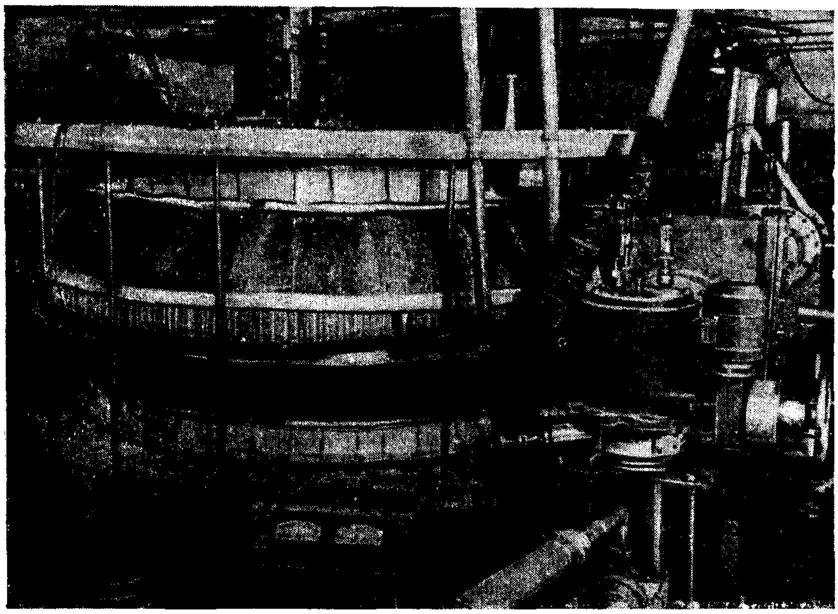


FIG. 9

sis, which have been presented here briefly, are a serious argument for believing that this approach represents a promising avenue of success. It should not be forgotten, however, that these analyses are based on a simplified physical picture of a discharge in which many important details have been neglected. This theory does not consider such displacements from the equilibrium state as are characterized by wavelengths smaller than the thickness of the skin layer and which evidently cannot be stabilized by methods which apply for long-wave perturbations.

It should also be noted that by its very nature the magnetohydrodynamic analysis is not suitable for analyzing such kinetic effects as the transition of electrons into a continuous acceleration mode in an electric field. Such processes can occur near the boundary of the pinch as a consequence of the low density of matter and the reduction in the retarding forces that the ions exert on the electrons. These processes, however, also occur inside the pinch since the energy spectrum of the electrons must include particles of energies considerably greater than the mean energy for which a transition to a continuous acceleration mode can take place, even with high values of N. As is well known, an accelerated beam of electrons can excite various kinds of plasma oscillations and thus change the character of the process. Other forms of disturbances are also possible which do not fit into the simple magnetohydrodynamic picture but which are a source of potential danger as far as maintenance of pinch stability is concerned.

9. We now turn to a consideration of the experimental results. In the first stages of the experimental work all the basic investigations were carried out in chambers made from insulating materials (glass, quartz, and porcelain). Because of the strong outgassing from these walls reliable results could be obtained with these chambers only when relatively high gas densities were used in the chamber and when the discharges were not too strong.

A study of the effects of a fixed longitudinal magnetic field on the behavior of slow discharges has shown that with a slow current rate of rise there is a paramagnetic effect in the plasma, such as has been discovered earlier by Soviet physicists in fast pulsed discharges. At low values of H_z this effect leads to the contraction of the pinch. The effect of a longitudinal magnetic field on the conductivity of the plasma is found to be weak. Regardless of the initial pressure, the intensity of the induced electric field, and the H_z, the conductivity is found to be approximately 1 to 3 × 10^{14} esu; this indicates a low plasma temperature in chambers with insulating walls. A study of the shape of the pinch by high speed movie photography and analysis of the oscillograms of the electrical and magnetic parameters in the discharge confirms the assumption of the pronounced instability of the process at small values of the ratio of H_z to H_φ. As the external field is increased, the discharge becomes more stable but the conductivity does not exhibit a significant rise. To ascertain the stability conditions for a pinch that is isolated from the walls, a number of experiments have been carried out with straight discharge tubes in which the discharge is started close to the axis and then expands towards the walls. These experiments con-

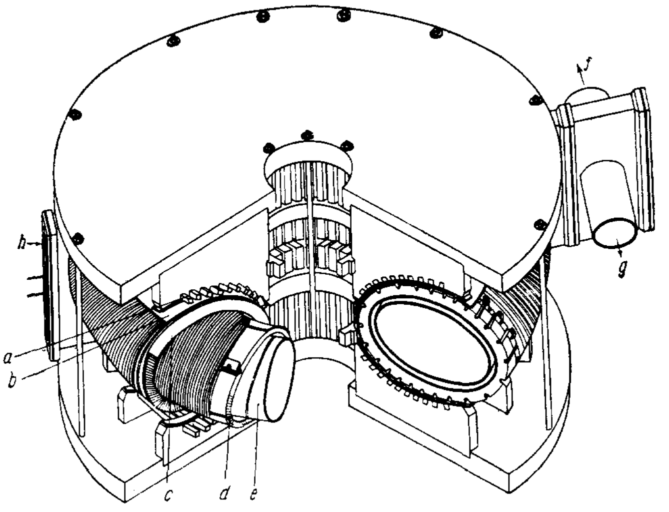


FIG. 10

firm qualitatively the theoretical conclusion that the pinch is stable if the inequality in (4) is satisfied. However, in these experiments, because of the high losses at the electrodes, there could be no hope of obtaining high plasma conductivity.

A further step was the transition to chambers with metal walls. It was expected that in chambers of this type it would be possible to maintain the purity of the gas during powerful discharges. Several large assemblies with metal toroidal chambers have been built at the Institute for Atomic Energy. A photograph of one of these systems, designed for investigation of high-current discharges over a wide range of external magnetic field, is shown in Fig. 9. In Fig. 10 is shown a cutaway diagram of the apparatus. The discharge takes place in a closed toroidal chamber made from stainless steel 0.2 mm thick. This is located inside a toroidal copper casing with walls 20 mm thick. The copper casing has two insulated cuts in a plane parallel to the axis of the toroid and one insulated cut along the generating line. The inside thin-walled chamber and the space between it and the casing are evacuated by separate vacuum systems. The diameter of the inner cross section of the discharge chamber is 0.5 m and the mean diameter of the toroid is 1.25 m. The chamber is the secondary winding of an air-core transformer. The primary winding is formed by 20 turns of thick copper strip wound on the casing. A shield, which encloses the casing, is used to eliminate stray magnetic fields. The coils which produce the longitudinal field are wound directly on the surface of the copper casing. The intensity of this field can be made as high as 12,000 oersteds. The electrical energy for the discharge circuit and the windings which produce the longitudinal field are capacitor banks (at peak voltage the total energy storage in these banks is 1.2 million joules). In the experiments carried out with the device described here the maximum current in the gas was 400 kiloamperes (at a discharge voltage of 0.45 kv and a longitudinal field of 12,000 oersteds).

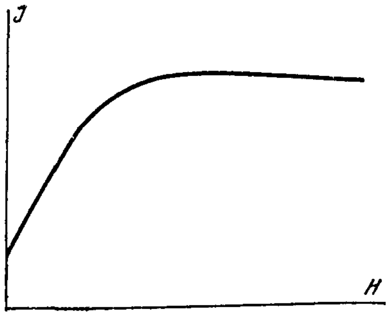


FIG. 11

The basic results obtained in the first stage of experimental work of discharge processes in metal toroidal chambers may be summarized as follows:

1. In hydrogen and deuterium at initial pressures ranging from 3×10^{-4} to 5×10^{-3} mm Hg the peak current of a discharge whose half period lies between 300 and 1200 μsec is approximately proportional to the initial discharge voltage and is only weakly dependent on gas density. As H_z increases, the current strength increases and then remains essentially constant. The general nature of the dependence of I_{max} on H_z is shown in Fig. 11.

2. At small values of H_z the pinch separates from the walls. As H_z increases the diameter of the pinch also increases. If $H_z \gg 0.2\, I_{max}/b$, where b is the chamber radius, the plasma column always remains in contact with the walls.

3. For small values of H_z the conductivity of the plasma (computed under the assumption that the current distribution is uniform over the cross section of the pinch) approaches the value 1×10^{15} esu when the pinch remains separated from the walls. In discharges in strong longitudinal fields, in which the plasma fills the entire cross section of the chamber, the conductivity falls to 1 or 2×10^{14} esu.

These results would seem to indicate that in the present experiments the electron temperature (as determined from the conductivity) was probably no higher than 15 — 25 ev.

It follows that even under conditions for which the pinch remains completely isolated from the walls the energy losses can still be very large; it is precisely for this reason that the plasma temperature does not reach the values predicted by theory. At the present time the mechanism for these energy losses is still not clear. Possible explanations are that the pinch is not sufficiently stable or that the impurity atoms evaporated from the chamber walls contaminate the plasma. These conclusions are merely preliminary ones since the experimental work with metal chambers is still in progress.

In the near future our main efforts will be directed toward the creation of conditions which reduce sharply any deleterious effects due to the presence of impurities in the plasma.

III. MAGNETIC TRAPS

10. Generally speaking the term "magnetic trap" can be applied to any device used to obtain extremely high temperatures in which magnetic confinement is used. However we will find it expedient to narrow the meaning of this terminology, applying it only to a definite type of system.

In the devices considered above the main agent responsible for confining the heated matter was the current maintained in the plasma by virtue of external voltage sources. This means that in such devices particles "hold on to each other" by means of the mutual self-consistent fields produced by the particles themselves. In this case the external magnetic fields fulfill the auxiliary role of a medicine used to treat the instability. In systems with high plasma currents the hydrodynamic pressure p is of order $H^2/8\pi$; hence the plasma is capable of exerting strong counter effects on the magnetic field distribution and this results in a number of characteristic instabilities.

In contrast to the above, we shall use the term magnetic trap to apply to systems in which the plasma confinement function role is played exclusively by the external field, with the plasma conduction currents remaining unimportant. Hence, in magnetic traps the quantity $8\pi p/H^2$ can be small compared with unity, i.e., the rarefied plasma may not have an important effect on the external magnetic field.

Various means can be used to obtain matter heated to high temperatures in magnetic traps. One method is to fill the magnetic system with fast ions injected from a powerful accelerator. Another method is to fill the trap with plasma and then heat this plasma by means of dynamic magnetic fields or high-frequency electromagnetic fields. Still another possibility is that of obtaining fast ions directly in the trap itself by using constant or alternating electric fields to accelerate ions derived from the plasma itself.

The most natural approach to the problem of magnetic traps would be to analyze the problem of the bounded motion of a single particle in an external field; then, having found a satisfactory solution to this problem, the next step would be to investigate the behavior of a large number of particles which comprise the plasma. In spite of its obvious shortcomings, this approach is very straightforward and, at the first stage, makes it possible to circumvent the difficulties associated with the formulation of a rigorous theory for the behavior of a plasma in complex fields.

The problem of devising such a magnetic trap which, at least in principle, would seem to allow of practical realization, has occupied many Soviet physicists. A stimulant to the discussion of this problem was the work of A. D. Sakharov and I. E. Tamm. In 1950 these investigators proposed the first concrete model for a magnetic thermonuclear reactor. In this version it was suggested that rarified deuterium be isolated and heated in a toroidal chamber in which a strong longitudinal magnetic field was produced by means of a coil wound on the outer surface of the chamber. However, this system has a fundamental defect when considered as a magnetic trap. Because the field inside the toroidal chamber is inhomogeneous, each particle executes a drift motion perpendicular to the field lines; this motion is terminated when the particles strike the chamber walls. The authors directed attention to this situation and proposed later that the drift motion could be eliminated through the use of the magnetic field of the plasma current.

Further work in this field confirmed the fruitfulness of the original idea and several types of magnetic systems were developed with which it was possible to confine particles to limited regions of space. As a result the experimental work on the development of magnetic traps became extremely important and promising. It should be noted, however, that the most important goal, the development of a trap which confines all particles, regardless of their direction or velocity, has still not been achieved and the question of whether such a system can be devised at all is still open.

11. The actual types of magnetic traps which have been studied up to this time can be divided into two basic classes:

(1) Traps with magnetic "stoppers" (mirror systems);

(2) Traps with limited drift.

A theoretical investigation of systems of the first type was initiated by G. I. Budker in 1953. Particles whose velocity directions form angles which are not too small with respect to the lines of force are reflected when they approach the strong field region and are thus trapped in the

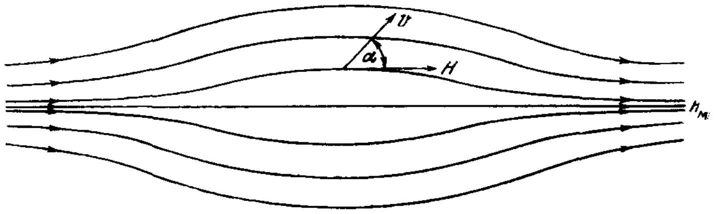


FIG. 12

magnetic system. For simplicity we shall assume that the field in the median plane is homogeneous. Suppose that the strength of this field is H_1 while the maximum intensity at the points of concentration of the force lines ("magnetic stoppers") is H_m. Under these conditions, if a particle in the region of homogeneous field is characterized by a velocity vector which lies within one of the cones defined by the condition

$$\sin\alpha < \sqrt{\frac{H_1}{H_m}},$$

in its subsequent motion the particle will pass through the region of maximum field and escape; however, if the initial velocity lies outside these cones the particle is trapped.

Let us assume now that a thermonuclear generator is to be built using a magnetic trap of the kind we have considered. An important question which immediately rises is that concerning the role of collisions between particles. It is apparent that even one collision will be sufficient to cause the velocity vector of the particle to fall into the escape zone. Hence the lifetime of particles in the plasma in a magnetic stopper trap will, in order of magnitude, be equal to the time between two Coulomb collisions between ions. In order that the energy generated in a system of this kind as a result of thermonuclear reactions be sufficient to compensate for the energy losses due to the escape of particles by virtue of Coulomb collisions the following condition must be satisfied:

$$\sigma_n W_n \sim \sigma_C kT.$$

In this expression σ_n is the effective cross section for the nuclear reaction, σ_C is the effective cross section for Coulomb collisions, W_n is the energy generated in each elementary nuclear fusion event.

Making use of this condition it is possible to estimate the minimum temperature at which the thermonuclear generator should begin to produce excess energy. For the D-T case this figure is on the order of tens of kilovolts; for pure deuterium it is on the order of 1 Mev. Thus, the use of pure deuterium in systems of these kinds is essentially hopeless as far as practical purposes are concerned. This conclusion is verified by more rigorous calculations, in which other kinds of losses are taken into account (bremsstrahlung and betatron radiation from fast electrons).

Theoretical investigations of the stability of a plasma in magnetic traps with plugs have been carried out at the Institute for Atomic Energy and indicate that there are perturbations of the equilibrium state which, themselves, are not stable. Pressure anisotropy in the plasma and pronounced deviations from the Maxwellian distribution for the particle velocity components along the lines of force constitute additional sources of instability in systems of this kind.

The mechanism for the formation of certain kinds of instabilities is related in an important way to the geometry of the magnetic field in the trap; it is therefore possible to have cases in which perturbations of a given kind can be stabilized in one kind of a trap and grow in other traps. For example, one kind of dangerous instability can arise in systems in which the plasma boundary has a negative curvature (Fig. 13). At points of negative curvature the plasma can leak out in the form of individual "tongues" which are perpendicular to the force lines. However this form of instability

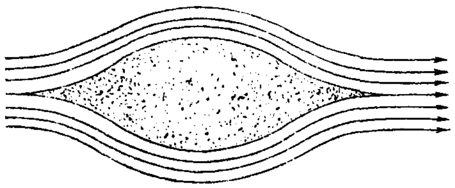


FIG. 13

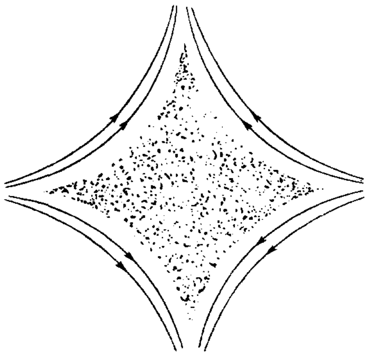


FIG. 14

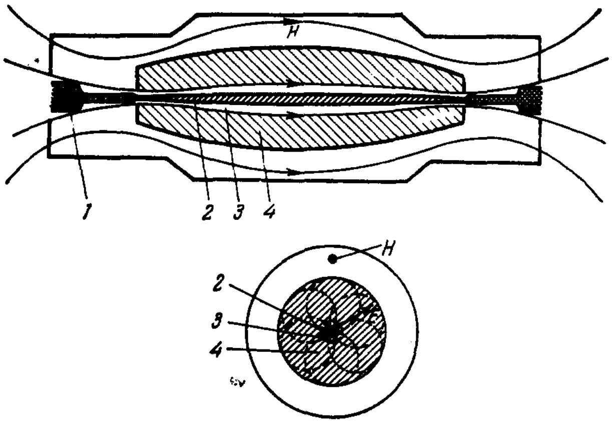


FIG. 15. 1) plasma source; 2) plasma beam; 3) region of strong electric field; 4) region of fast ion motion.

is probably not characteristic of systems in forced lines with positive curvature (Fig. 14). With an increase in the ratio p/H^2 there is a marked increase in the danger associated with all kinds of instabilities. Even if traps with magnetic stoppers turn out to be unfeasible from the practical point of view, it is possible that they can still be used to demonstrate the feasibility of a thermonuclear reaction at small values of $8\pi p/H^2$.

An experimental investigation of traps with magnetic stoppers was carried out at the Institute for Atomic Energy several years ago. The first experimental system was designed for studying the storage of fast ions extracted from a cylindrical plasma pinch which was produced along the axis of the magnetic system (Fig. 15). The pinch, with an ion concentration of 10^{13}, was produced by means of an arc discharge in a longitudinal field. In Fig. 16 is shown a general view of the apparatus with which experiments of this kind are being carried out at the present time. The length of the vacuum chamber is 2 meters; the magnetic field strength at the center is 8500 oersteds while the magnetic field at the stoppers is 12,000 oersteds. During operation of the ion source a pressure of 10^{-7} mm Hg is maintained by means of titanium pumps. A voltage of 40 kv is used to accelerate the ions between the pinch and the side walls of the chamber. The main purpose of these experiments is the determination of the lifetime of fast ions for various ion densities in the magnetic system. The mean lifetime of these ions can be determined from the rate at which the density decreases after the accelerating voltage is switched off.

The results of the first experiments indicate that in these systems the lifetime of a plasma containing fast ions is of the order of several milliseconds. This lifetime increases with improved vacuum conditions and with an increase in the value of H.

In the summer of the past year construction was completed at the Institute for Atomic Energy of a large experimental device with magnetic stoppers. This device will be used to study external injection of particles. The D^+ ions are accumulated by dissociation of D_2^+ molecular ions which are injected into the central section of the trap. The molecular ions are dissociated by collisions with molecules or atoms of the residual gas or by interactions with the ions of the rarified deuterium plasma which has previously been produced in the chamber. In Fig. 17 is shown a schematic diagram

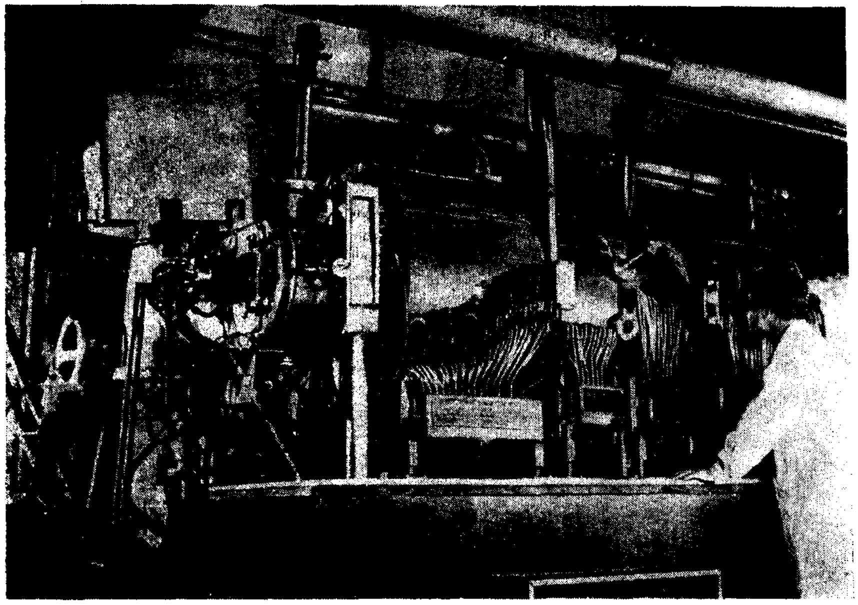


FIG. 16

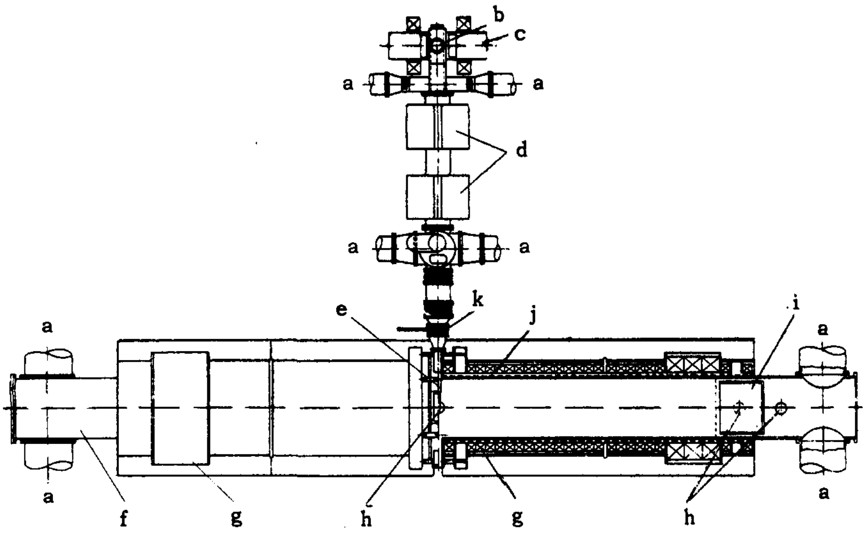


FIG. 17. a) to evacuation system; b) ion source (+ 220 kv); c) source magnet; d) quadrupole lenses; e) magnetic channel; f) chamber; g) winding; h) titanium evaporator; i) electrode (-15 kv); j) heating chamber; k) valve.

of this apparatus. The distance between the centers of the stoppers is 12 meters; the inner diameter of the vacuum chamber is 1.4 meters. The field intensity in the central region can be as high as 5,000 oersteds and the field in the stoppers can be raised to 8,000 oersteds. An intense beam of D_2^+ ions is obtained from an arc source in a transverse magnetic field. The D_2^+ ions, accelerated by a voltage of 200 kv, are focused and injected into the magnetic trap by means of a system of electric and magnetic fields. It is expected that after the system is tuned up that the current of D_2^+ ions entering the vacuum chamber will be several hundred milliamperes. It is hoped that with this intensity for the injected ion beam the density of D^+ ions in the trap will be as high as 10^{12}.

An experimental study has also been started on systems with geometries such as that shown in Fig. 14. A field of this kind is interesting for several reasons: in particular, as has been indicated above, it is hoped that in this case a higher degree of plasma stability can be obtained with respect to certain kinds of perturbations.

12. There are several other ways of evaluating magnetic systems which can be used as magnetic traps. The main problem is to ascertain the conditions under which the drift velocity of the particles in the inhomogeneous field does not lead to their escape from a restricted region of space. In Figs. 18 and 19 are shown magnetic systems which illustrate two possible approaches to the solution of this problem. In the system shown in Fig. 18, the magnetic field along the straight sections is "corrugated" (by using non-uniform windings along the chamber surface). Particles moving in an inhomogeneous field of this kind are subject to rotational drift motion so that their trajectories rotate about the axis of the field.

Thus, in spite of the presence of the curved end sections a particle which makes a complete circuit does not approach the walls since the rotation of the trajectories in the linear sections balances out the effect of drift in the curved end sections.

An example of another method in which the drift is limited through the use of rotation about the force lines is the system shown in Fig. 19. This is a torus which is deformed into the form of a figure eight.

It is easy to see that both systems described here suffer from the same shortcomings as a trap with stoppers. These systems are capable of confining only those particles whose velocity vectors lie within a definite region of allowed directions. Particles with small longitudinal velocities which enter the curved spaces will strike the walls as a

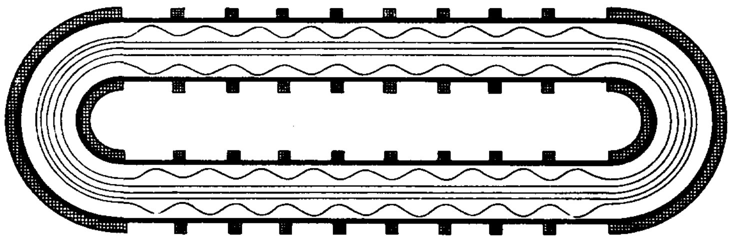


FIG. 18

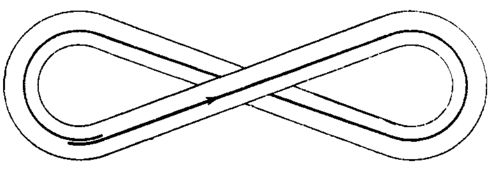


FIG. 19

result of drift motion before escaping from this space.

However, it appears that future developments of these principles of compensating drift (corrugation of the field and involution of the field lines) may make it possible to reduce the range of directions for particle escape so that the properties of these systems will begin to approximate those of ideal traps.

The methods described above for magnetic traps are based on the application of constant or slowly varying (in time) magnetic fields. Theoretical studies indicate the broad possibility of confining and isolating a plasma by means of high-frequency electromagnetic fields. In the present case the term "high-frequency" means that the oscillation period of the field is considerably less than the times characteristic of the behavior of the plasma. The frequencies in question are tens of megacycles and higher. The force which confines the plasma in this kind of field is determined by the mean square value of H rather than the instantaneous value.

It would seem that high-frequency fields can be used most effectively in conjunction with fixed magnetic fields used as auxiliary fields for eliminating energy losses due to corpuscular beams. For example, high-frequency electromagnetic fields can be used as a "stopper" to confine particles which have escaped along the field lines from the region of strong fixed magnetic field.

The feasibility of confining plasmas by means of field combinations of this type has been verified experimentally in a small device at the Institute for Atomic Energy. The practical prospects for the use of high-frequency fields for isolating a heated plasma seem to be rather unfavorable at the present time, however, because of the high energy consumption required to maintain these fields. Nevertheless, investigation of various versions of high-frequency confinement are of considerable interest.

High-frequency electromagnetic fields can also be used as a means of heating plasma. Greatest interest in this connection now attaches to an investigation of the possibility of using ion cyclotron resonance effects. Research in this field, which has been carried out in the U.S.S.R., is described in a report presented by the Ukrainian Physico-Technical Institute at the Geneva Conference in 1958.

CONCLUSION

In his speech at the first Geneva Conference on the Peaceful Uses of Atomic Energy the President of the Conference, Dr. Homi Bhabha, said:

"The historical period we are just entering, in which atomic energy released by the fission process will supply some of the power requirements of the world, may well be regarded one day as the primitive period of the atomic era. It is well-known that atomic energy can be obtained by the fusion process as in the H-bomb and there is no basic scientific knowledge in our possession today to show that is is impossible for us to obtain this energy from the fusion process in a controlled manner. The technical problems are formidable, but one should remember that it is not yet fifteen years since atomic energy was released in an atomic pile for the first time by Fermi. I venture to preduct that a method will be found for liberating fusion energy in a controlled manner within the next two decades. When that happens the energy problems of the world will truly have been solved forever for the fuel will be as plentiful as the heavy hydrogen in the oceans."

Three years have passed since this prediction was made and now, before our eyes, we begin to see the first rough outlines of the scientific foundation on which the methods of solving the problem of controlled fusion will probably be based. This foundation has been laid as a result of the experimental and theoretical work which has been carried on in recent years in the U.S.S.R., U.S.A., England, and other countries. For the first time this work has been the subject of open discussion on an international scale; in this respect it probably represents the most important step which has been made in the solution of this problem. The importance of this step is greater than that of the results of any of the individual research work which, as yet, have not brought us very much closer to the final goal.

We do not wish to appear pessimistic in evaluating the future of our work but, at the same time, we must not underestimate the difficulties which must be overcome along the path to the achievement of controlled nuclear fusion. In the final analysis the chief difficulty is the fact that in a light material such as rarified plasma any instability effect develops at a tremendous rate. It is difficult to build any automatic monitoring device which could rapidly compensate for deviations from the equilibrium state. Hence it would appear that the most rational approach to the problem would be a system in which all forms of instability are eliminated beforehand.

It is probable that the solution of the problem will be easier in the case in which the reaction of the plasma on the magnetic field is small, i.e., when $p \ll H^2/8\pi$.

Turning now to a more general appraisal of the situation, it can be said that no one of the presently-known ideas has been shown to be decisively better than any other as far as the production of a controlled fusion reaction is concerned. For this reason, in the near future research should be carried out along the widest possible front.

An important factor in ensuring the success of this research will be the continuation and further development of the international scientific cooperation which has been started by the Geneva Conference. The solution of the problem of thermonuclear fusion will require a maximum concentration of intellectual effort and the mobilization of very sizeable material and technological facilities. This problem would seem to have been specially created to stimulate cooperation between scientists and engineers of various countries, working in accordance with a general program and continuously exchaning the results of their calculations, experiments and technical developments.

The international fusion of research work on the problem of controlled fusion will undoubtedly lead to a considerable reduction in the time required for us to reach the desired goal.

Translated by H. Lashinsky